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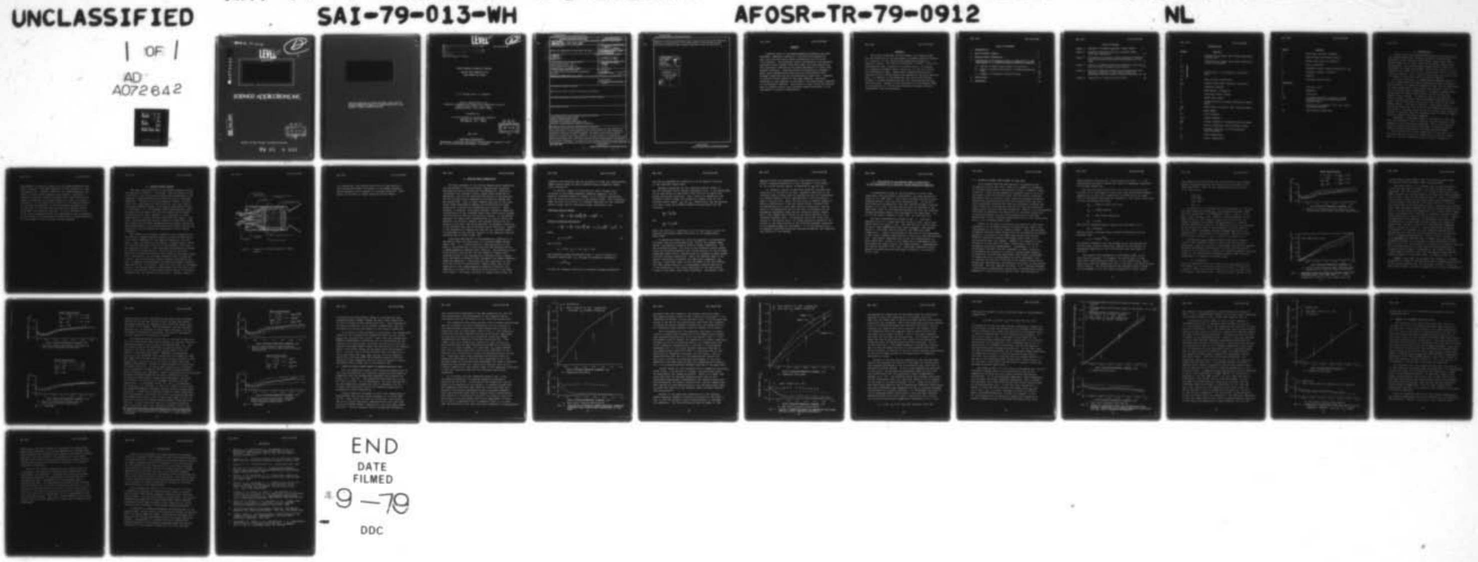

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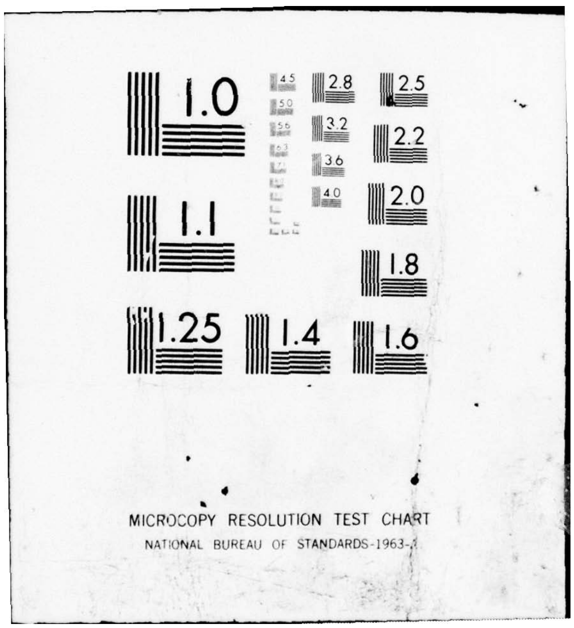
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AFOSR INTERIM SCIENTIFIC REPORT:

MIXING AND COMBUSTION IN HIGH SPEED AIR FLOWS

P. T. Harsha and R. B. Edelman

Science Applications, Inc.
Combustion Dynamics and Propulsion Technology Division
20335 Ventura Blvd., Suite 423
Woodland Hills, California 91364

Prepared for

Air Force Office of Scientific Research
Bolling Air Force Base
Washington, D.C. 20332

May 1979

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFOSR-TR- 79-0912	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): MIXING AND COMBUSTION IN HIGH SPEED AIR FLOWS		5. TYPE OF REPORT & PERIOD COVERED: INTERIM rept. April 1978 — April 1979
		6. PERFORMING ORG. REPORT NUMBER: SAI-79-013-WH
7. AUTHOR(s): P T HARSHA, R B EDELMAN		8. CONTRACT OR GRANT NUMBER(s): F49620-77-C-0044
9. PERFORMING ORGANIZATION NAME AND ADDRESS: SCIENCE APPLICATIONS, INC, 20335 VENTURA BLVD, SUITE 423, WOODLAND HILLS, CALIFORNIA 91364		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2308A2, 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BLDG 410, BOLLING AIR FORCE BASE, D C 20332		12. REPORT DATE: May 1979
		13. NUMBER OF PAGES: 39
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

SUDDEN EXPANSION (DUMP) BURNER
INTEGRAL ROCKET/RAMJET ENGINE
RECIRCULATING REACTING HIGH-SPEED FLOWS
MODELING SUDDEN-EXPANSION COMBUSTOR FLOWFIELD

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of a modular model for the prediction of the performance of sudden expansion burners as a function of the controllable parameters relevant to combustor design. The model is based upon a concept in which the recirculation zone, treated as a stirred reactor, is coupled to a parabolic boundary layer formulation for the flow outside the recirculation zone. Hydrocarbon oxidation kinetics and turbulent kinetic energy models are employed in the model development. In addition to the parabolic-flow and stirred reactor

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elements, a module representing the fuel injection process has been developed. Results of the application of the modular model to the analysis of cold-flow and reacting-flow dump combustor experimental data are described.

SUMMARY

A modular model of the sudden-expansion combustor has been developed, combining a parabolic, directed-flow computation and a well-stirred reactor model representing the recirculation region(s). The parabolic module incorporates a two-equation turbulent kinetic energy turbulence model, and both modules use the quasiglobal formulation for rapid computation of finite-rate chemical reactions. Coupling between the modules is through a shear layer representation which provies the parabolic-flow boundary conditions and the stirred-reactor feed rates. Compared to unified elliptic models of the dump combustor, the major advantage of this approach is the greatly increased detail possible in the combustor analysis. This detail in turn allows the development of chemical kinetic and flowfield models applicable to the refinement of elliptic formulations.

ABSTRACT

This report describes the development of a modular model for the prediction of the performance of sudden expansion burners as a function of the controllable parameters relevant to combustor design. The model is based upon a concept in which the recirculation zone, treated as a stirred reactor, is coupled to a parabolic boundary layer formulation for the flow outside the recirculation zone. Hydrocarbon oxidation kinetics and turbulent kinetic energy models are employed in the model development. In addition to the parabolic-flow and stirred reactor elements, a module representing the fuel injection process has been developed. Results of the application of the modular model to the analysis of cold-flow and reacting-flow dump combustor experimental data are described.

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LIST OF FIGURES

NOMENCLATURE

SYMBOL	MEANING
a	Coefficient in shear layer width expression (growth rate)
b	Coefficient in shear layer width expression (initial thickness)
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$, C_{μ}	Coefficients in two-equation turbulence model
C_F	Skin friction coefficient
C_{PR}	Prandtl model eddy viscosity coefficient
D	Combustor diameter
h	Dump height = $(D_3-D_2)/2$
K	Turbulent kinetic energy
l	Shear layer width
l_k	Turbulent kinetic energy dissipation length scale
l_{PR}	Width scale in Prandtl eddy viscosity model
M	Mach number
P_o	Total pressure
P_s, P	Static Pressure
P_{RK}	Prandtl number for turbulent kinetic energy
r	Radial coordinate; with subscript radius
Δr	Distance from wall to first parabolic flow grid point
T_o	Total temperature
T_s	Static temperature

SYMBOL	MEANING
u	Axial mean velocity component
$\bar{u}$	Mass-average axial mean velocity
v	Radial mean velocity component
x	Axial coordinate
ε	Turbulent kinetic energy dissipation rate
μ_T	Turbulent dynamic viscosity
ρ	Density
τ	Turbulent shear stress
SUBSCRIPTS	
2	Combustor inlet
3	Combustor
C_L	Centerline
dsl	Dividing streamline (boundary between directed flow and stirred reactor in modular model)
i	Grid point in parabolic flow just inside dividing streamline
RZ	Recirculation zone value

1. INTRODUCTION

Current and future airbreathing propulsion system concepts are tending toward lower weight and smaller volume designs. An example is the integral rocket/ramjet engine which uses a common combustor for rocket boost and sustained ramjet flight. Unfortunately, the current design trends create stringent requirements for higher performance from smaller volumes, but the combustion processes are not well enough understood to optimize combustor designs. Thus, combustor development has been carried out largely by employing costly cut-and-try methods.

The basic difficulty in understanding combustor behavior is the coupling between turbulent mixing and reaction kinetics. This problem is not unique to combustor flows, but is encountered in other systems where flow, mixing, and reaction times are all of the same order of magnitude, for example, external burning devices for thrust and/or control and gas dynamic and chemical laser systems. In addition, many of the reacting flows of general interest involve condensed phase species and large scale recirculation zones such as are found in the "dump" burner concept. Problems in ignition, flame stabilization, combustion efficiency, and flowfield and combustion instabilities also occur in the dump burner as well as in many other combustion systems of interest, and these problems need to be better understood to support engineering judgement.

Consequently, continued research is required in both subsonic and supersonic flows in order to gain the necessary understanding of the controlling mechanisms. Only in this way can effective design principles be developed to provide optimum propulsion system performance over wide operating ranges.

The objective of the work summarized in this report is to eliminate the deficiencies just described and provide a sound basis for effective combustor design criteria, through the

development of analytical models for the sudden-expansion combustor flowfield. The major emphasis in this program is on the development of a "modular" model for the sudden expansion combustor, in which proved computational elements, including a parabolic flowfield analysis procedure and a perfectly-stirred reactor formulation, are coupled together to model the overall flowfield. In this report the features of the modular approach are reported and progress in the development and application of the model to cold-flow and reacting-flow combustor data is described. This work has involved, and will continue to involve, close coordination with the experimental work in progress at the Air Force Aero Propulsion Laboratories at Wright-Patterson Air Force Base, as well as other related programs.

2. MODULAR MODEL CONCEPT

The basic characteristics of the sudden expansion burner are depicted in Figure 1. In essence, the key feature of the flow field is the recirculation region just downstream of the expansion, separated from the directed flow by the dividing streamline. Because of this recirculation region, in which there is no characteristic flow direction, the flow field in the sudden expansion burner is in general described by elliptic equations; i.e., the boundary layer approximations cannot be applied to the whole flow and the elliptic Navier-Stokes equations must be used. However, it is possible, at least conceptually, to divide the flow field into two regions. The first, the directed flow region, consists of that part of the flow between the dividing streamline and the burner centerline. The second region is the recirculating flow region, and the two regions are coupled through the conditions at the dividing streamline.

The concept of the modular approach to the computation of the flow in a sudden expansion burner involves the application of available techniques to the separate regions of the flow field. Thus, the directed flow region is treated using a parabolic finite difference solution of the boundary layer form of the equations of motion. The recirculation regions are treated as perfectly stirred reactors, with the reactor feed rate defined by the species diffusion flux across the dividing streamline. The shape of the dividing streamline must be specified a priori; the resulting wall static pressure distribution may then be compared with experiment and another dividing streamline shape specified, if necessary. Since the flow field is in general elliptic, the modular approach approximates the true flow field, and the specification of the species fluxes across the dividing streamline must be carried out iteratively. However, despite

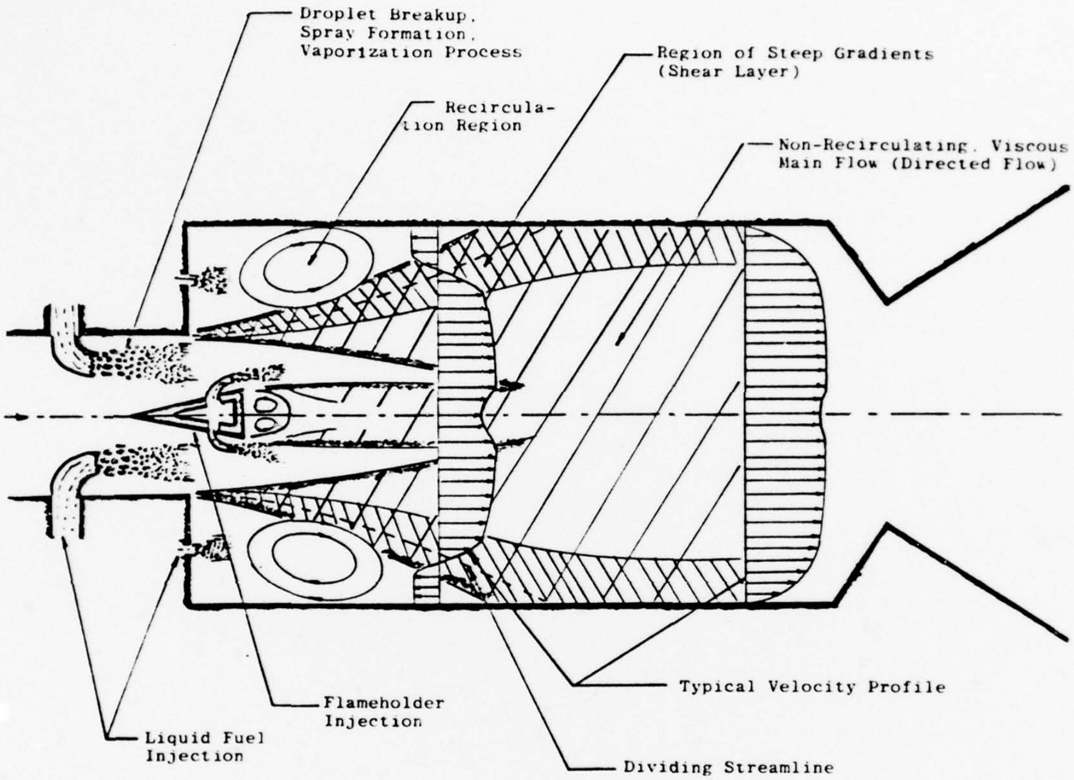


Figure 1. Schematic of Sudden Expansion (Dump) Burner

its limitations, this method does allow the application of well-tested and proved flow models to the sudden expansion burner geometry, and is capable of yielding parametric information of interest in sudden expansion burner design.

3. MODULAR MODEL FORMULATION

The basic elements of the current modular model formulation are the parabolic finite-difference computational technique developed by Boccio, Weilerstein and Edelman [1], modified to incorporate the turbulent kinetic energy model developed by Harsha [2], used for the directed-flow portion of the analysis, and the stirred reactor computation developed by Edelman and Weilerstein [3]. Both of these elements make use of the quasi-global model developed by Edelman and Fortune [4] for rapid computation of finite-rate hydrocarbon air kinetics. These elements, or modules, are coupled together through a simplified representation of the turbulent shear layer which exists between the directed flow and the recirculation region. In the modular approach, the shear layer representation is used to define the gradients in velocity, species, and enthalpy between the two regions of the flow, thus providing both the boundary conditions on the directed flow and the stirred reactor feed rates. Details of the mathematical formulations used for the flowfield region are discussed in this section; details of the numerical analysis procedure may be found in Ref. [5].

A detailed description of the mathematical formulation of the modular model has been given in a previous AFOSR interim report, Ref. 6 , in which results of the application of the model to the prediction of both cold flow and reacting flow in a sudden-expansion combustor were reported. One observation from these previous results was that the algebraic length scale formulation used in the one-equation turbulent kinetic energy model developed by Harsha [2] was inadequate for sudden expansion combustor geometries. The reason for this inadequacy is that there are two major characteristic length scales that can be identified in the sudden-expansion combustor flowfield, one applying to the main flow (directed flow) and one to the shear layer region. The radial variation in length scale across the

combustor that develops from the existence of these two characteristic length scales cannot be easily modeled using an algebraic length scale formulation.

To provide a means of accounting for radial length scale variation in the sudden-expansion combustor geometry, the two-equation turbulence model of Launder, et al. [7] was incorporated into the directed flow portion of the modular model. This turbulence model involves the solution of transport equations for the turbulent kinetic energy and the turbulence energy dissipation rate:

Turbulent Kinetic Energy

$$\rho u \frac{\partial k}{\partial x} + \rho v \frac{\partial k}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r}\left(\frac{\mu_T r}{Pr_k} \frac{\partial k}{\partial r}\right) + \mu_T \left(\frac{\partial u}{\partial r}\right)^2 - \rho \varepsilon \tag{1}$$

Turbulence Energy Dissipation

$$\rho u \frac{\partial \varepsilon}{\partial x} + \rho v \frac{\partial \varepsilon}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{\mu_T r}{Pr_\varepsilon} \frac{\partial \varepsilon}{\partial r}\right) + C_{\varepsilon 1} \frac{\varepsilon}{k} \mu_T \left(\frac{\partial u}{\partial r}\right)^2 - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \tag{2}$$

where

$$\mu_T = C_\mu \rho \; k^2/\varepsilon \tag{3}$$

and in which

$$C_\mu = 0.09, \; C_{\varepsilon 1} = 1.40, \; C_{\varepsilon 2} = 1.95$$

The turbulence energy dissipation rate, ε, can be related to a turbulent length scale, ℓ_k, through the Kolmogorov hypothesis

$$\varepsilon \propto k^{3/2}/\ell_k$$

so that the transport equation for turbulence energy dissipation

can also be regarded as a description of the spatial variation of the turbulent length scale.

Boundary conditions for the turbulent kinetic energy, k, and the turbulent kinetic energy dissipation rate, ε, are established in the same manner as described in Ref. [6] for the mean total energy and species equations. Thus, values are assumed for the turbulent kinetic energy and dissipation length scale for the stirred reactor region, k_{rZ} and ε_{RZ}, respectively, and the gradient in k and ε along the dividing streamline established from the relations

$$\frac{\partial k}{\partial r} = \frac{k_i - k_{rZ}}{\ell}$$

and

$$\frac{\partial \varepsilon}{\partial r} = \frac{\varepsilon_i - \varepsilon_{RZ}}{\ell}$$

where the subscript i represents the first grid point inside the directed flow region module and $\ell = ax+b$ is the assumed shear layer width.

It should be pointed out that this approach is substantially different from that described in Ref. [6] for the modular model using a one-equation turbulent kinetic energy formulation. For the one-equation model, the value of the turbulent kinetic energy along the dividing streamline was related directly to the dividing streamline shear stress, obtained from the assumed dividing streamline skin friction coefficient. While the approach used in the present formulation introduces two additional parameters, k_{RZ} and ε_{RZ}, it has been found, as will be shown in the next section, that this method results in a considerably reduced sensitivity of the prediction to the values specified for the coefficients a and b in the shear layer width expression. Furthermore, this

approach allows the investigation of the sensitivity of the overall flowfield prediction to the "intensity" of the mixing in the stirred reactor region, as measured by k_{RZ} and ε_{RZ}.

For combustor regions in which the parabolic directed flow computation is carried to the wall, boundary conditions on the turbulent kinetic energy and its dissipation rate are established in a manner similar to other applications of the two-equation model to ducted flow. Thus, the wall value of kinetic energy is directly proportional to the wall shear stress, obtained from the specification of a wall skin friction coefficient, and the value of the dissipation rate at the wall is obtained from the Kolmogorov hypothesis using the wall turbulent kinetic energy and a local length scale related to the law-of-the-wall for a turbulent boundary layer. It should be noted that within the context of the modular model for sudden expansion combustors the effects of the specification of the flowfield boundary conditions at the combustor wall are *negligible: it is the specification* of boundary conditions along the dividing streamline that dominates the solution to the problem.

4. APPLICATION OF THE MODULAR MODEL TO PREDICTION OF THE PERFORMANCE OF A PROTOTYPE SUDDEN-EXPANSION COMBUSTOR

A comprehensive study of the performance of center dump combustors, with and without flameholders, has been reported by Craig, et al. (Ref. [8]). This paper includes results for both premixed and wall fuel injection configurations. In the wall fuel injection configuration, fuel was injected through 8 equally spaced, 0.14 cm dia. orifices located 12.07 cm upstream of the dump plane, while in the premixed configuration fuel was injected through spraybars located 1.5 m upstream of the dump plane. For all of the results reported in Ref. [8] , the fuel was JP-4.

The basic configuration studied in Ref. 8 involved a combustor L/D of 3, a dump area ratio A_3/A_2 of 2.25, and an exit nozzle area ratio A_2/A_3 = 0.40. Two sets of inlet airflow rates and inlet total temperatures were used throughout, with nominal values of 1.45 kg/sec and 0.73 kg/sec, and 555^{o}K and 722^{o}K, respectively. A major contribution of this work is the measurement of wall static pressure distributions in both cold flow and reacting flow. This report represents one of the few investigations in which these data, crucial to the comparison of experimental data with analytical model results, have been reported. Supplementing the results reported in Ref. [8] , additional unreported static pressure distributions have been made available to the authors by Dr. Craig.

4.1 EFFECTS OF MODEL COEFFICIENTS IN COLD FLOW

As is obvious from the description of the modular model in Section 3 and in Ref. [6] , there are a number of parameters in the model which must be specified in order to compute a given flowfield. These include geometric parameters such as the size and shape of the recirculation zone, and the initial thickness and spread rate of the shear layer along the dividing streamline between the recirculation zone and the directed flow, and flowfield parameters including the effective turbulent intensity and scale within the recirculation zone and the effective turbulent shear stress along the dividing streamline. Thus it is of considerable importance to determine the sensitivity of the model predictions to these parameters, as well as the sensitivity of the model predictions to inlet condition specification and to the coefficients used in the turbulence model itself.

Several of the model coefficients are related to each other, although it is not always possible to establish the form of the relationship in an a priori, general fashion. Thus, the dividing streamline turbulent shear stress level can be expected on physical grounds to be related to the shear layer growth rate and the effective turbulent intensity and length scale level in the recirculation zone, for example. However, for purposes of this evaluation of the effects of model coefficients, each of the parameters was varied independently. Furthermore, it is of considerable interest from the standpoint of model evaluation to determine the accuracy with which a reacting dump combustor flowfield can be predicted using model coefficients established by comparison with a corresponding cold flow experiment, both to evaluate the effects of reaction on the overall flowfield and because more detailed data are generally available for nonreacting flowfields. The data reported by Craig, et al., Ref.[8], includes a broad range of experimental conditions for geometrically similar combustors, in both cold flow and hot flow, and includes wall

static presure distributions, which earlier work (Ref. 6) has indicated can be used to assess the effects of parameter variations on the model prediction.

For the cold flow calculations, the cold flow data obtained by Craig et al. (Ref. [8]) in an area ratio 2.25 center-dump combustor geometry at an inlet total temperature of 552°K and an air mass flow of 1.45 kg/sec were used for comparison. The initial conditions for the calculations were thus:

$$P_{S_2} = 2045.3 \text{ lb/ft}^2 \text{ (0.97 atm)}$$

$$T_{S_2} = 930^{\circ}\text{R (516.}^{\circ}\text{K)}$$

$$U_2 = 895 \text{ ft/sec (273 m/sec)}$$

$$M_2 = 0.603$$

The initial turbulent kinetic energy level was taken to be

$$K_2 = 0.03(U_2)^2$$

and the initial turbulent kinetic energy dissipation rate was obtained from

$$\varepsilon_2 = 1.69(k_2)^{3/2}/r_2$$

An adiabatic combustor wall was assumed in all calculations and the wall skin friction coefficient (applied in the regions upstream and downstream of the recirculation zone) was taken to be 0.003.

The values of the parameters in the modular model can in most cases be bounded: for example, the coefficient b in the shear layer width expression must lie in the range $0<b<r_2$, while similarly a must be bounded such that at the end of the recirculation zone $0<ax+b<r_3$. The recirculation zone turbulent kinetic energy can be assumed to be of the order of magnitude of $(U_2)^2$, while

the length scale which defines the recirculation zone turbulent kinetic energy dissipation rate should be of the order of the dump step height. Thus for the configuration used by Craig et al. [8] we have

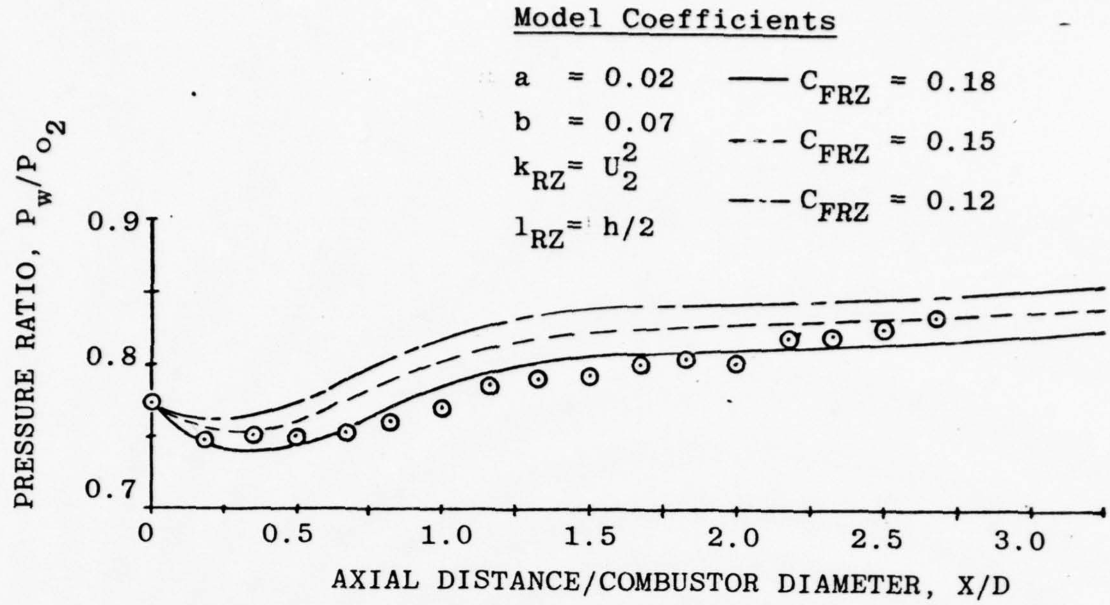
$$0<a<0.32$$
$$0<b<0.167$$
$$k_{Rz} \simeq (U_2)^2$$
$$l_{Rz} \simeq h$$

An initial set of calculations of the Craig et al. cold flow data was carried out using C_{FRz}, the dividing streamline "skin friction" coefficient, as a parameter, with a = .02, b = 0.07, $k_{Rz} = (U_2)^2$, and $l_{Rz} = h/2$. Results of these computations are shown in Fig 2a, for a range in C_{FRz} from 0.12 to 0.18. As would be expected, an increase in C_{FRz} results in a greater velocity retardation effect on the directed flow, as is indicated by the increase in value of the parameter $(u_{cl}-\bar{u})/\bar{u}$ shown in Fig. 2b. Here $\bar{u}$ represents the mass-average velocity in the directed flow: for uniform flow $(u_{cl}-\bar{u})/\bar{u}=0$, while for a parabolic velocity profile, $u/u_{cl}= 1-(r/r_w)^2$, $(u_{cl}-\bar{u})/\bar{u} = 0.5$.

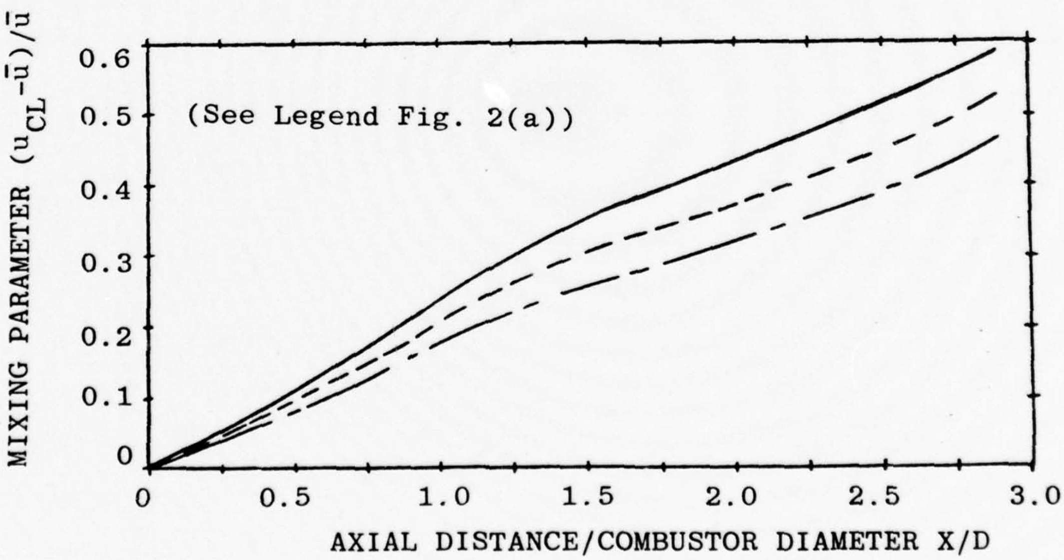
Although the C_{FRz} parameter cannot be directly related a priori to the turbulent viscosity level along the dividing streamline, since the viscosity is determined through the computed divinding streamline turbulent kinetic energy and dissipation rates, it is of interest to compare the computed turbulent viscosity levels to that which would be obtained using an eddy viscosity formulation, for example the Prandtl model

$$\mu_T = \rho C_{PR} l_{PR} \Delta u$$

Using the computed values of μ_T and Δu, for the C_{FRz}=0.18 case, and taking l_{PR} to be the shear layer width scale l, results in a range of values of the coefficient C_P of $0.37< C_{PR}<.042$ along the length of the shear layer. These are within a factor of two



a) Effect of Recirculation Zone "Skin Friction" Coefficient on Wall Static Pressure Distribution



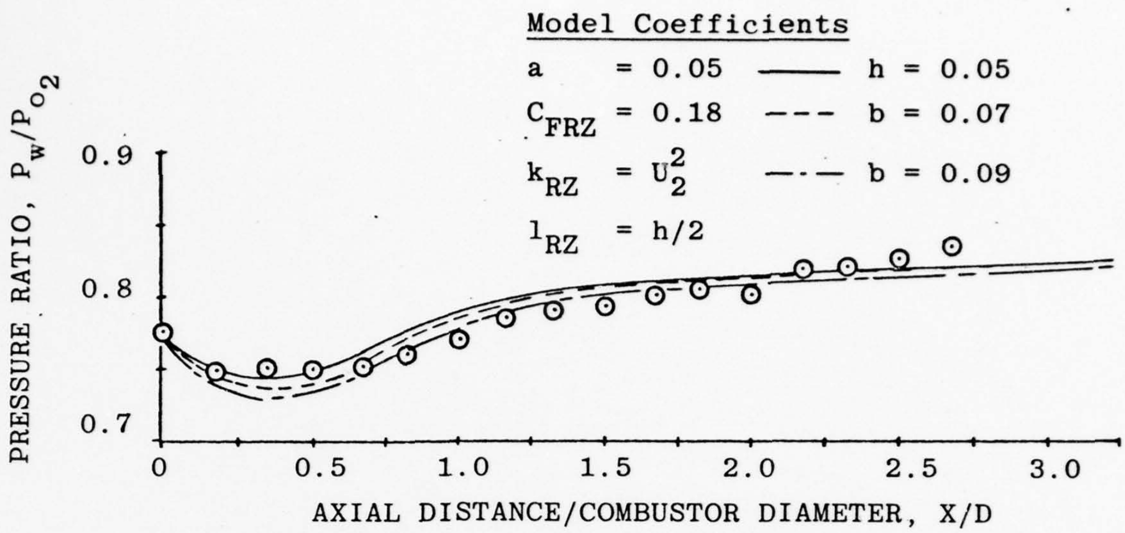
b) Effect of Recirculation Zone "Skin Friction" Coefficient on Velocity Profile Development

FIG. 2. PARAMETER VARIATION EFFECTS ON MODULAR MODEL COLD FLOW PREDICTION, DATA FROM CRAIG 8 , L/D=3, A_3/A_2=2.25, A^*/A_3=0.40, T_{oI}= 1000°R, M_I=0.603

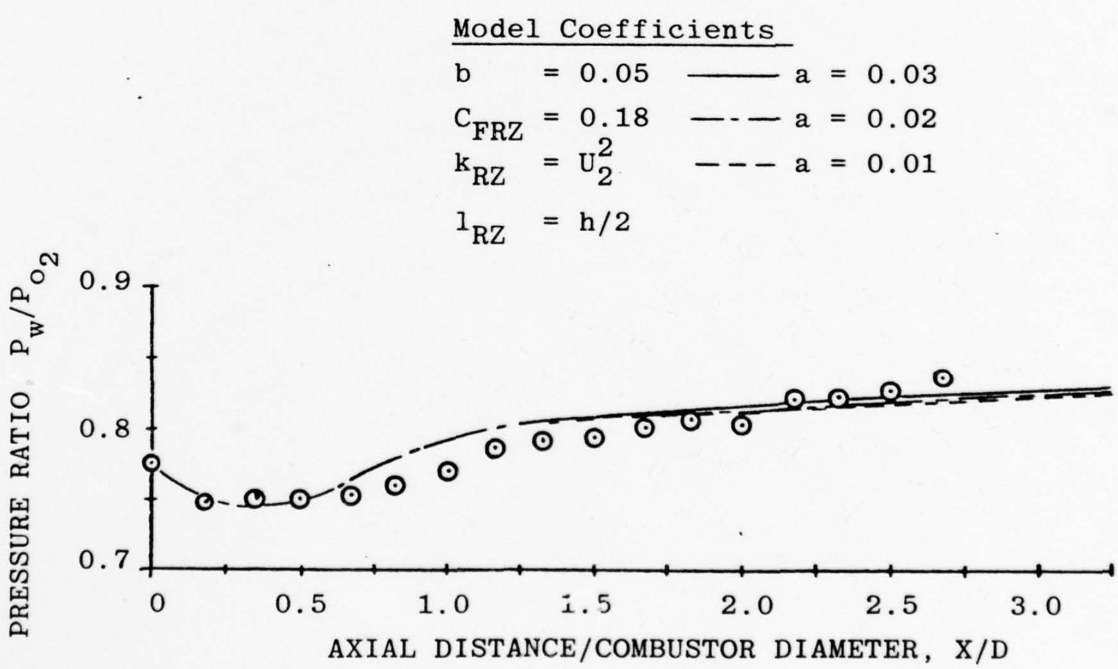
of the values of C_{PR} commonly used for turbulent shear layer calculation using the Prandtl eddy viscosity model.

From thse results, it is evident that the best prediction of the cold flow data of Craig et al. [8] is achieved using C_{FRz}=0.18. The next parameter to be varied is the initial shear layer thickness, b, and the results of variation of this parameter over a range .05<b<.09 are shown on Fig. 2c. Here it is evident that the major effect of the initial shear layer thickness is on the pressure distribution in the early portion of the flow, just downstream of the dump plane (x/D=0). Decreasing the initial shear layer thickness decreases the initial pressure drop observed both in the data and in the predictions, at a given value of C_{FRz}. This is consistent with a decrease in turbulent viscosity level along the dividing streamline, which does in fact occur. However, the magnitude of the decrease is considerably less than would be predicted by a simple eddy viscosity model with change in length scale, because of the use of a two-equation turbulence model to obtain the viscosity. As the shear layer thickness is decreased, the transport of both turbulence energy and its dissipation rate from the recirculation zone into the directed flow is increased proportionally. The net effect, however, is to decrease the turbulent kinetic energy along the dividing streamline, because of an increase in enery dissipation at this point in the flow. This results in a decrease in turbulent viscosity, but a decrease smaller than that which would be predicted by a simple viscosity model. Consequently, the overall effect of a ±30% change in initial shear layer thickness on the predicted pressure gradient is relatively small, as shown in Fig. 2c.

Changes in the shear layer growth rate constant, a, produce essentially no change in the predicted static pressure distribution, as can be seen from Fig. 2d, for the range .01<a<03. Since the shear layer length to initial thickness ratio for this configuration



c) Effect of Shear Layer Initial Thickness on Wall Static Pressure Distribution



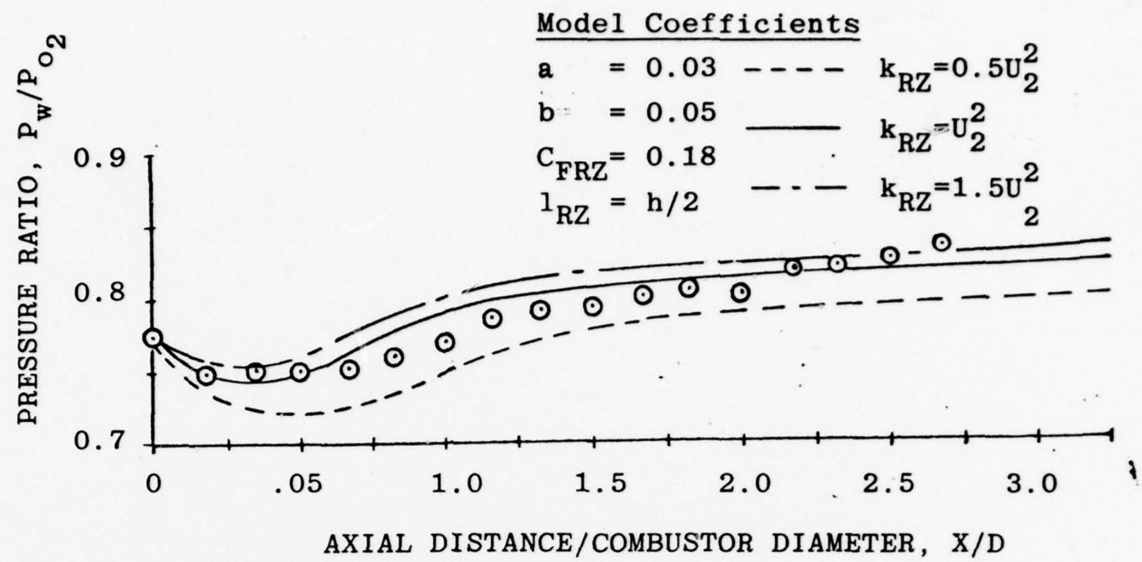
d) Effect of Shear Layer Growth Rate on Wall Static Pressure Distribution

FIG. 2. CONTINUED

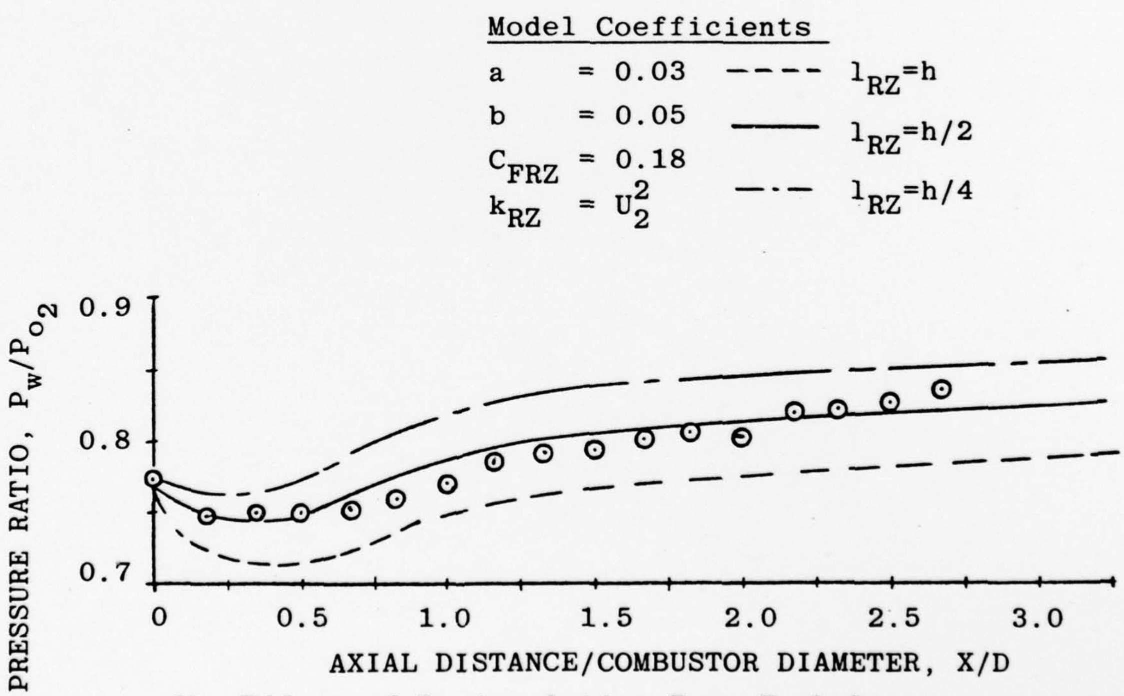
(with b=0.05) is 15.3, the width of the shear layer increases 46% for a=0.03 and only 15% for a=0.01, so that the initial thickness dominates the transport rate across the shear layer over most of its length. This observation, and the relative insensitivity of the model to shear layer thickness, with the two-equation turbulence formulation, provides an explanation for the insensitivity observed in Fig 2d.

The remaining parameters involved in the model formulation are the recirculation zone kinetic energy, k_{rz} and the effective dissipation length scale in the recirculation zone, l_{rz}. For the computations so far described, k_{rz} was set equal to the square of the inlet velocity, and l_{rz} was taken to be h/2, where h is the dump step height. Parametric calculations with k_{rz} as the parameter were carried out for $0.5u_2^2<k_{rz}<1.5u_2^2$.* Note that since the recirculation zone dissipation rate $\varepsilon_{rz}=1.69 (k_{rz})^{3/2}/l_{rz}$, the value of ε_{rz} for each of these cases was adjusted accordingly. Results of these parametric calculations are shown on Fig. 2e. As can be seen from Fig. 2e the results of this parametric evaluation show a greater initial pressure drop occurring as k_{rz} decreases. This is indicative of an increasing dividing streamline turbulent viscosity coefficient as the recirculation zone kinetic energy level decreases. Similarly, the effects of variation of the assumed recirculation zone length scale, l_{rz} are shown in Fig. 2f: as l_{rz} is decreased, for given k_{rz}, ε_{rz} increases, so that the viscosity level along the dividing streamline decreases and the initial pressure drop decreases. It should be noted with regard to these comparisons that the parametric variations involved in the results decribed are somewhat artificial, since in both cases shown in Figs. 2e and 2f the effective dividing streamline shear stress was held constant. Clearly the specification of dividing streamline shear stress must affect the turbulent intensity level within the recirculation zone, since physically it is the conversion

*A value of 1.5 u_2^2 is physically unrealistic but has been used to determine the sensitivity of the model to large parameter variations



e) Effect of Recirculation Zone Turbulent Kinetic Energy Level on Wall Static Pressure Distribution



f) Effect of Recirculation Zone Turbulence Dissipation Rate Length Scale on Wall Static Pressure Distribution

FIG. 2. CONCLUDED

of directed flow mean kinetic energy to recirculation zone turbulent kinetic energy through the shear layer region that drives the mixing in the recirculation zone. This coupling has not been accounted for in the present computations, but will be modeled in further development of the modular formulation.

As a result of these parametric calculations, the coefficients chosen for the reacting flow computations were a=0.03, b=0.05, C_{FRZ}=0.18, $k_{rz}=(u_2)^2$ and l_{rz}=h/2. These cold flow computations, besides establishing a preliminary set of coefficients for the reacting flow calculations, also show that the use of the two-equation turbulence model reduces the sensitivity of the combustor model to the values chosen for the shear layer coefficients a and b. The wall static pressure predictions are sensitive to the values chosen for C_{FRZ}, k_{RZ}, and l_{RZ}, with the apparent sensitivity involving both the dividing streamline viscosity implied by these parameters and the relative transport rates of turbulent kinetic energy and its dissipation rate.

4.2 EFFECT OF MODEL COEFFICIENTS IN PREMIXED REACTING FLOW

With the appropriate model coefficients determined from the cold flow calculations just outlined, predictions were made for comparison with the premixed dump combustor data reported by Craig et al. Ref.[8] . The predictions were made for a fuel-air ratio of 0.053. In the experiments, the fuel used was JP-4; for the computations propane was used to represent the fuel. A simple one-step global finite rate chemistry model was incorporated in these computations.

Initial conditions included an inlet total temperature of 554°K (997°R) and an inlet static pressure of 1.83 atm (3881 lb/ft^2). With a mass flow rate of 1.57 kg/sec (3.45 lb/sec), the inlet velocity and static temperature were 159 m/sec (521 ft/sec) and 543°K (977°R), respectively; the inlet Mach number was 0.351. Initial turbulent kinetic energy and dissipation

rate values were established in the same manner as for the cold flow calculations, and the geometry of the combustor and recirculation zone was the same as in the cold flow calculations.

Both combustion efficiency and wall static pressure distribution data are available for this configuration, and the results of the modular model calculation of these quantities are shown in comparison with the experimental data in Fig. 3. The combustion efficiency shown was computed from the mass-average temperature at each axial location in the calculation, using the JANNAF temperature-rise combustion efficiency definition [9] . The "ideal" exit total temperature required for this calculation was obtained from the data tabulations provided to the authors by Dr. R. R. Craig of AFAPL; for these data, T_{T_5} (ideal)=2178°K. Note that in these comparisons, data points are shown for the fuel/air ratio 0.053 value at which the computations were carried out. These data points were obtained from plotted values of combustion efficiency vs fuel-air ratio presented in Ref. [8] . The band shown for each data point represents the range of observed combustion efficiencies as a function of fuel-air ratio and is a better indication of the overall trend of the combustion efficiency vs fuel-air ratio data than are the individual data points themselves.

It is evident from the comparison shown in Fig. 3 that the model overpredicts the observed combustion efficiency, particularly for x/D<3. In evaluating this comparison, and the others to be described in this section, it should be noted that the combustion efficiency data shown for X/D=1 and X/D=2 were obtained in different experiments using a shortened combustor. Since the cold flow L/D=3 results indicate that a recirculation zone length of 1.55 diameters (obtained from Drewry's cold flow data [10] for the step height used in the experiments of Craig et al. [8]) is appropriate for a combustor L/D=3, it is clear that the flowfield in the L/D=1 and L/D=2 combustors is significantly

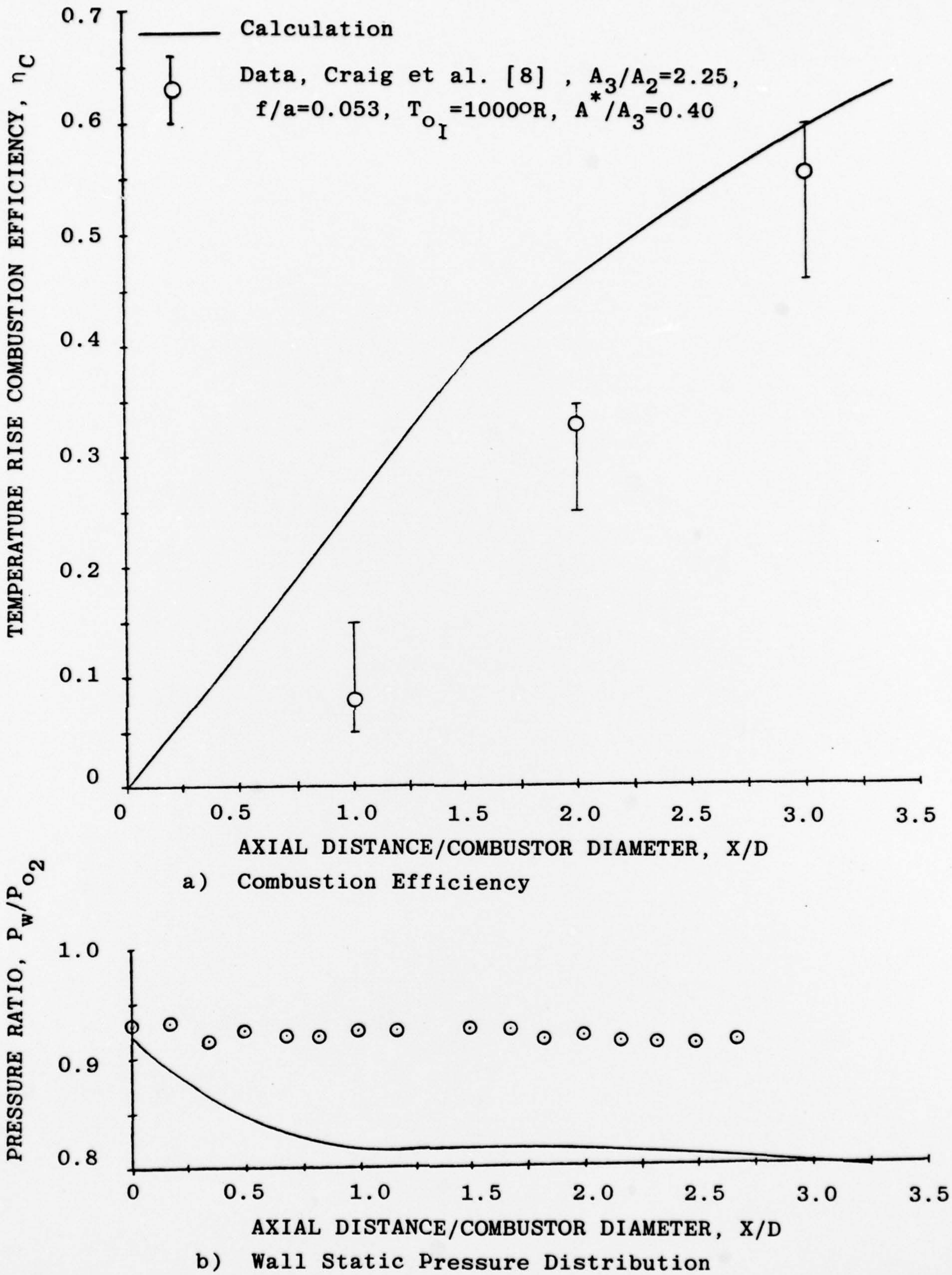


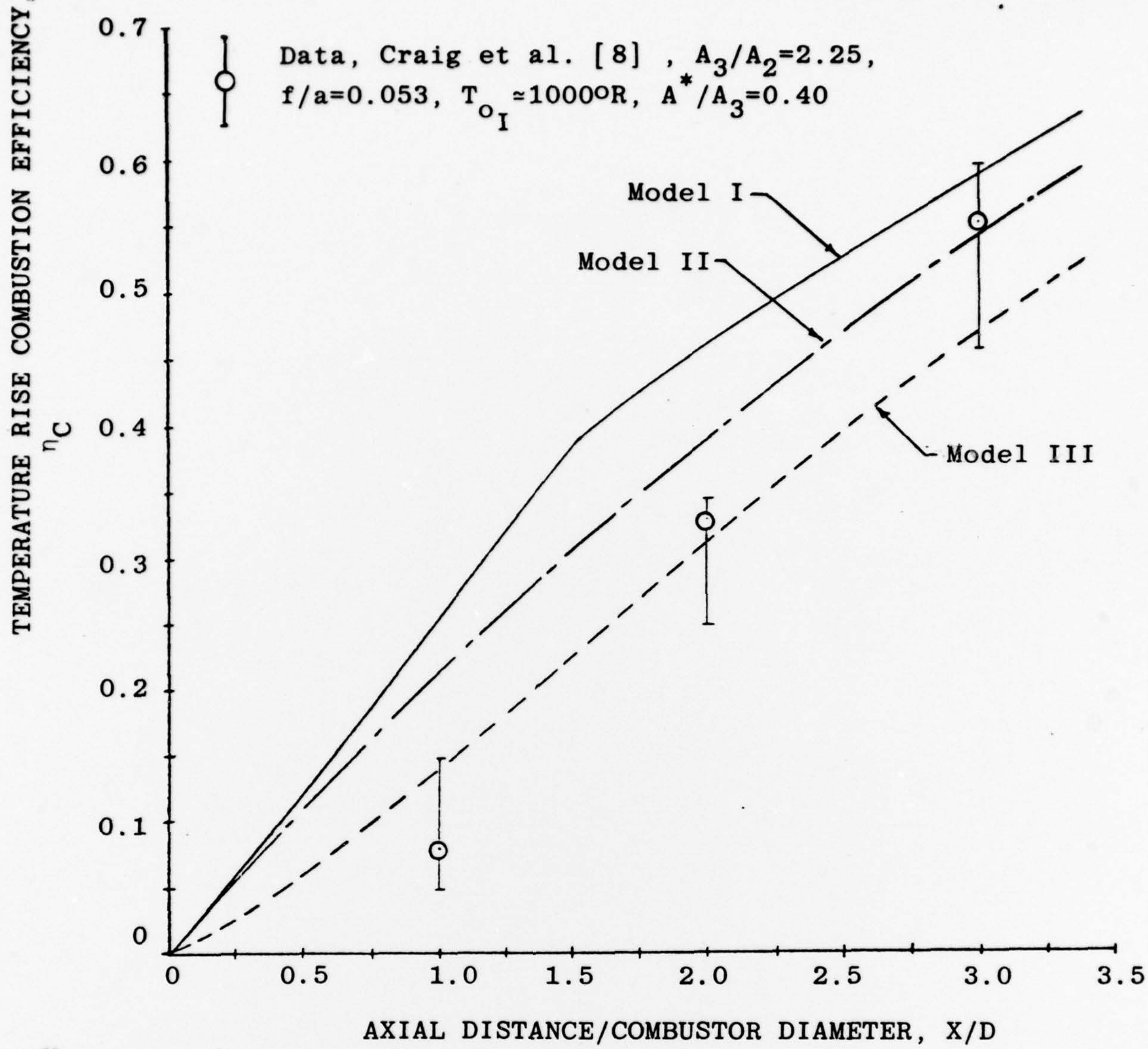
FIG. 3. CALCULATION OF REACTING SUDDEN EXPANSION COMBUSTOR FLOWFIELD USING COEFFICIENTS ESTABLISHED IN COLD FLOW

different than that assumed in the present analytical model. The computed results shown in Fig. 3 show a discontinuity in the combustion efficiency vs axial distance curve: this discontinuity occurs at the end of the recirculation zone where the transport of energy and species abruptly becomes zero (as appropriate for the isoenegetic wall boundary condition assumed in the model).

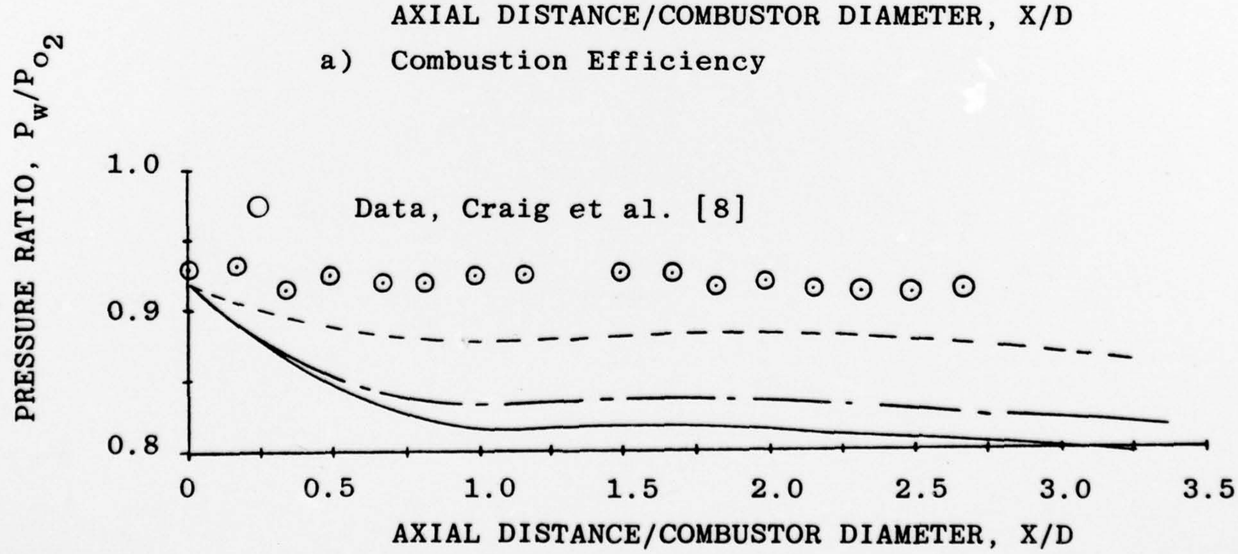
The overprediction of the combustion efficiency for $X/D<2$ results in significant differences in the computed and measured wall pressure distributions, as is also shown in Fig. 3. This discrepancy tends to support the combustion efficiency comparison irrespective of the differences between the computational and actual combustor configurations as outlined in the preceding paragraph; that is, the sharp pressure reduction observed in the computational results for $X/D<1$ is consistent with an over-prediction of combustion efficiency in this region. Here it should be noted that while in the computational results the wall static pressure is normalized with respect to the total pressure at the dump plane the data are normalized with respect to a total pressure measured somewhat upstream of the dump plane.

A major reason for the overprediction of combustion efficiency shown in Fig. 3 is the use of a simple, one-step global model to characterize the combustion process. Since it is known from other work that the one-step chemistry model used in this calculation significantly underpredicts the ignition delay time and overpredicts the overall reaction rate, further computations were carried out with modifications to the one-step global model to assess the effects of the chemistry model on these reacting flow calculations.

Results of two additional computations of the reacting sudden expansion combustor flowfield configuration are shown on Fig. 4, with the original results (denoted model I) included for comparison. For the calculations shown as model II, the



a) Combustion Efficiency



b) Wall Static Pressure Distribution

FIG. 4. EFFECT OF COMBUSTION MODEL ON COMBUSTION EFFICIENCY AND WALL STATIC PRESSURE DISTRIBUTION

pre-exponential coefficient in the global model was arbitrarily reduced for X/D<1.55, returning to its original value for X/D>1.55; the model used in the well-stirred reactor recirculation zone module was unchanged. While this modification has the desired effect of reducing the predicted combustion efficiency, and increasing the computed wall static pressure, the shapes of both the combustion efficiency and wall static pressure curves are incorrect, particularly for $\frac{X}{D} \leq 2$. Thus an alternate approach was taken for the model III calculations: the original one-step model was used in the directed flow, while the pre-expoential coefficient for the recirculation zone was decreased. As can be seen from Fig. 4, this model produced a considerable improvement in both the shape and level of the combustion efficiency curve for $X/D \leq 2$, as well as in the wall static pressure distribution, at the cost of some accuracy in the prediction of combustion efficiency at X/D=3.

Because of the fast kinetics inherent in the one-step model used in the directed-flow portion of the model III calculations, the flowfield downstream of the recirculation zone (X/D>1.55) is effectively mixing limited. In all of the computations described to this point, the two-equation turbulence model has been used with coefficients that are essentially those recommended by Launder et al. [7] , the exception being the exchange coefficient for the dissipation rate, Pr_ε, which was taken to be 1.0 instead of the value of 1.3 used by Launder, et al. These coefficients have been established for use in nonreacting flowfield calculations, and other researchers have suggested the use of slightly different coefficients for reacting flowfields. To investigate the effects of the turbulence model coefficients on the reacting flowfield prediction using the present model, computations were carried out using the coefficients suggested by Hutchinson, et al. [11] :

$$C_\mu = 0.09,\ C_{\varepsilon 1}=1.44,\ C_{\varepsilon 2}=1.92,\ Pr_k=0.90,\ Pr_\varepsilon=1.22,$$

which can be compared to the coefficients used in the preceding computations:

$$C_\mu=0.09,\ C_{\varepsilon 1}=1.40,\ C_{\varepsilon 2}=1.95,\ Pr_k=1.00,\ Pr_\varepsilon=1.00,$$

from which it can be seen that the most substantial changes are in the kinetic energy and dissipation rate exchange coefficients. These differences will reduce the diffusion of dissipation rate, ε, while increasing that of the turbulent kinetic energy. As the results shown in Fig. 5 indicate the net effect of the differences between turbulence model coefficients is to increase the directed flow mixing rate, as is evidenced both by the increased level of combustion efficiency, and by the change in the predicted static pressure distribution. On the other hand, the small differences between the two turbulence model predictions of combustion efficiency in the recirculation zone region, $X/D<1.55$, can be taken to indicate that the changes inherent in the use of the turbulence model coefficients of Hutchinson, et al. [11] have little effect on the overall transport across the dividing streamline shear layer.

Also shown on Fig. 5 is the effect of decreasing the effective dissipation length scale in the recirculation zone on the combustion efficiency and wall static pressure distribution calculations: as in the preceding comparison, these computations use the model III global chemistry formulation, with a reduced pre-expoential rate coefficient within the sitrred reactor model of the recirculation zone. In the cold flow calculations, a change of effective recirculation zone length scale l_{RZ} from $l_{RZ} = h/2$ to $l_{RZ} = h/4$ had a substantial effect on the wall static pressure distribution, as seen, for example, in Fig. 2f, with decrease in the effective length scale resulting in reduced transport across the dividing streamline shear layer.

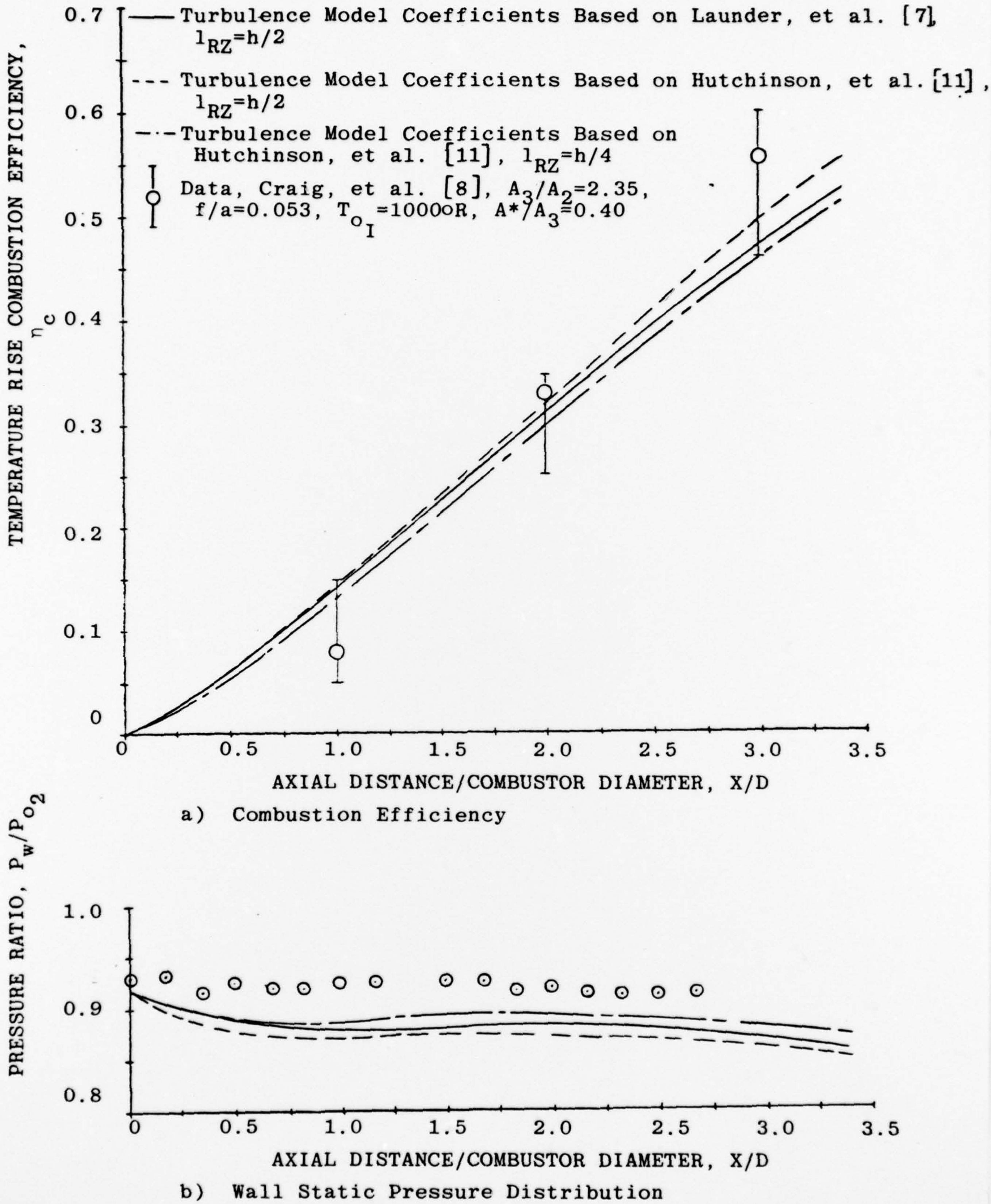
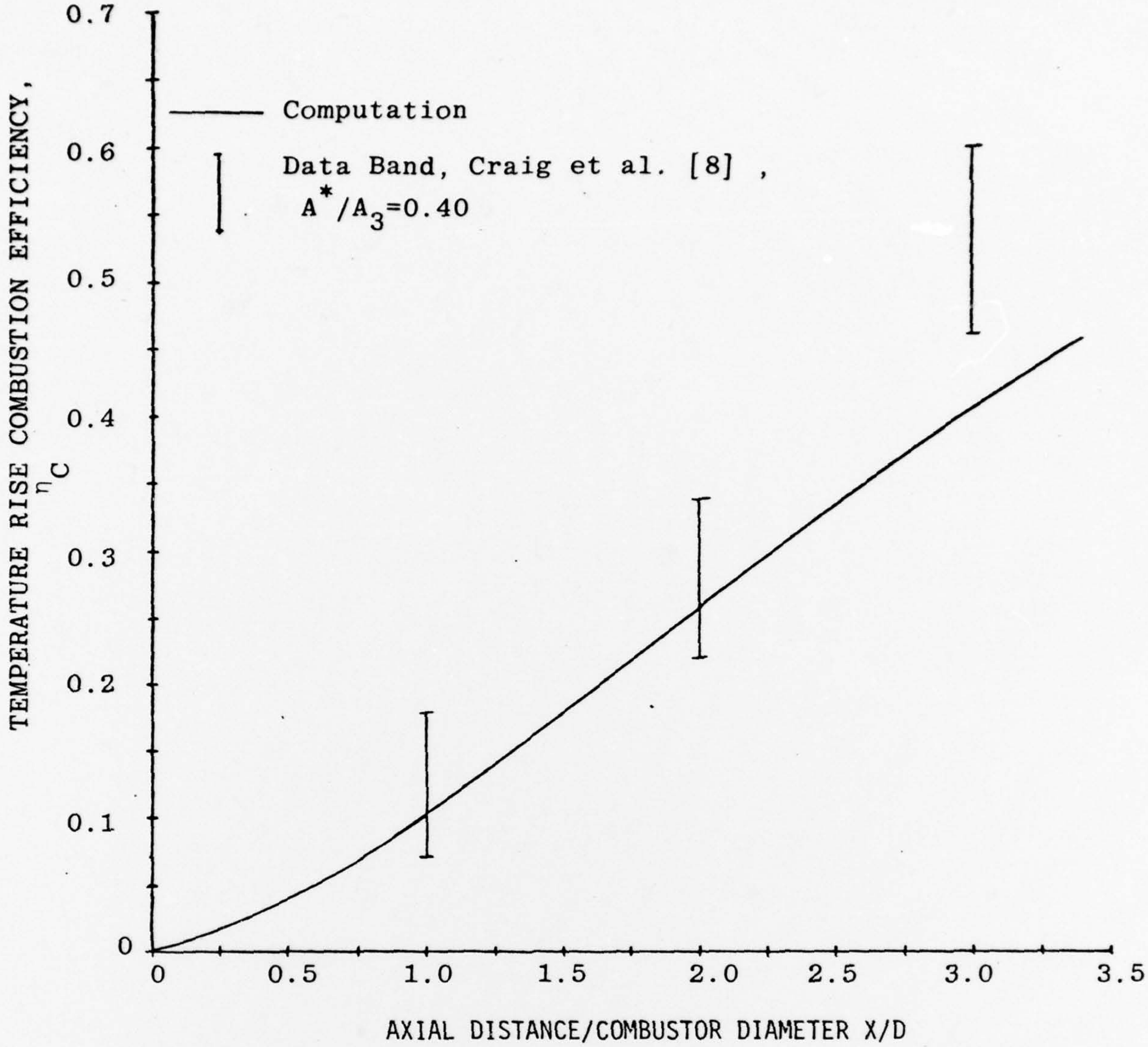


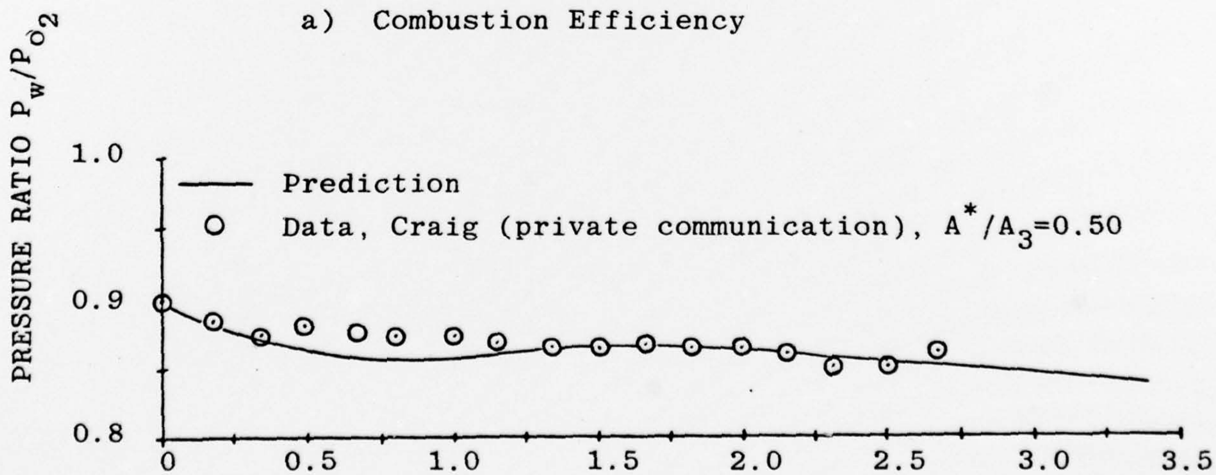
FIG. 5. EFFECT OF TURBULENCE MODEL AND RECIRCULATION ZONE BOUNDARY CONDITION ON CALCULATED COMBUSTION EFFICIENCY AND WALL STATIC PRESSURE DISTRIBUTION

This effect is still apparent in the reacting flow results in Fig. 5, but is substantially reduced, as is clear from a comparison of the results shown in Fig. 5 with those shown in Fig. 2f.

Although the results shown in Figs. 4 and 5 indicate a reasonably good level of agreement with the data of Craig, et al., particularly in view of the expanded scale used for the static pressure comparisons, all of the predictions show a characteristic static pressure decline followed by a region of relatively uniform and then slowly declining pressure. This behavior does not seem to appear in the experimental data. However, other data obtained by Craig using the same combustor configuration does show the characteristic behavior just described. These data were obtained for premixed fuel and air in a combustor identical to that used for the comparisons so far described ($L/D=3$, $A_3/A_2=2.25$) except that an area ratio 0.50 convergent nozzle was used instead of the $A^*/A_3=0.40$ nozzle used to obtain the experimental results previously shown. From the calculational standpoint, the differences between the two sets of data involve the inlet Mach number and mass flow rate. To determine whether the typical pressure ratio behavior observed in the previous results would also be observed for the initial conditons appropriate to the $A^*/A_3=0.50$ data, a computation was made using as initial conditions an inlet total temperature of 554^oK (997^oR), an inlet static pressure of 1.83 atm (3881 lb/ft^2), an inlet mass flow rate of 1.80 kg/sec (3.45 lb/sec) and an inlet Mach number of 0.401. The model III global kinetics formulation was used, with the turbulence model coefficients of Hutchinson, et al. [11] and $l_{RZ} = h/2$. Results of this computation are shown in Fig. 6. In the absence of data on combustion efficiency as a function of L/D for this configuration the data bands for the $A^*/A_3=0.40$ results are again shown, for comparison. The important observation is that the characteristic wall static pressure behavior observed in the $A^*/A_3=0.40$ comparisons is again observed, but for this



a) Combustion Efficiency



b) Wall Static Pressure Distribution

FIG. 6. COMPARISON OF PREDICTIONS WITH DATA FOR $A^*/A_3=0.50$ COMBUSTOR, PREMIXED, $f/a=0.053$, $T_{o_I} \simeq 1000^\circ R$

A^*/A_3=0.50 case it is in remarkably good agreement with the experimental data.

4.3 SUMMARY OF PARAMETER VARIATION STUDY

The results of these calculations show that, while the introduction of the two-equation turbulence model results in two additional coefficients compared to the model described in Ref. 6 in which a one-equation turbulence model was used, the resulting predictions show a markedly reduced sensitivity to the values chosen for the dividing streamline shear layer initial thickness and spread rate coefficients. Cold flow calculations show that the most sensitive coefficients are those which describe the shear stress level along the dividing streamline, C_{FRZ}, and the turbulent intensity level and turbulence dissipation length scale within the recirculation zone, k_{RZ} and ε_{RZ}, respectively. However, although k_{RZ} and C_{FRZ} have been treated as independent parameters in the work reported herein, they can be related to each other based on physical arguments. This coupling will be investigated in future work on the modular formulation.

For reacting flow, the comparisons show that, at least for the data used for the present work, the modeling of the completeness of reaction within the recirculation zone region has a strong effect on the predicted results. In this work, using a very simple one-step global finite rate model in both the directed flow and recirculation zone regions, good results were achieved only when the recirculation zone reaction rate was reduced by several orders of magnitude. For the cases in which good results were achieved, a recirculation zone combustion efficiency of 50-60% is indicated.

With the chemistry model used in the present computations, the flowfield downstream of the recirculation zone is essentially mixing limited. However, alteration of the turbulence model

coefficients from the original set, developed for nonreacting flowfield calculations, to a set recommended for reacting flowfield computations, produced little change in the overall results. Similarly, the sensitivity of the computations to the value assumed for the recirculation zone dissipation length scale was considerably reduced in reacting flow compared to nonreacting flowfield calculations.

Overall, the results obtained with the modular model incorporating a two-equation turbulence model formulation are encouraging. Calculations of reacting flow carried out using constants established in a geometrically similar cold flow configuration show a reasonable level of agreement with reacting flow data. The inaccuracies observed in the reacting flow prediction can be related to either the inability of a one-step global chemistry model to accurately predict the overall progress of the chemical reactions occuring in a combustor flow, or to the effects of a significant level of unmixedness in the stirred reactor region. This role of numixedness in the stirred reactor region will be addressed in future work on modular model development.

5. FUTURE WORK

Work on the development and exploitation of the modular model will continue, with emphasis on the continuing development of characterization of the turbulent mixing and chemical kinetics in sudden expansion combustor flowfields. It is worth noting in this regard that the reacting flow calculations presented here (which use a global finite rate kinetics model) averaged approximately $1\frac{1}{2}$ minutes run time on an IBM 3033 computer; three to four iterations were involved to obtain convergence in the stirred reactor-directed flow iteration. Thus the inclusion of fast routines utilizing more detailed kinetics formulations is of interest in order to maintain the attractive run time characteristics of the modular model.

Close cooperation with Drs. F. D. Stull and R. R. Craig of AFAPL will continue to be maintained in order to analyze and interpret AFAPL sudden expansion combustor data using the modular model. As was noted earlier in this report, the results presented here make use of unpublished AFAPL static pressure distribution data made available to the authors by Dr. Craig; these data are invaluable in the modular model development.

In addition to further development and exploitation of the modular model, further work in this area will include the development of a spray combustion model, utilizing the two-phase flow equations for the detailed description of the spray combustion process. Development of a unified (elliptic) formulation, taking advantage of the modeling techniques which have proven efficacious in the modular formulation, will also continue.

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